Date: December 31, 2015

EIC Detector R&D Progress Report

Project ID: eRD2
Project Name: Magnetic Field Cloaking Device
Period reported: from **July 2015** to **December 2015**
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Abstract

The Electron Ion Collider will collide electrons and hadrons. These collisions will be very asymmetric (due to the different momenta of the incoming particles) and yield a large number of final state particles at high pseudorapidities. A magnetic field oriented transversely to the beam line could significantly improve the momentum resolution for these particles over using only the fringe field of a solenoid. However, the collider beam has to be shielded from transverse fields to avoid deflection and depolarization. This project aims at demonstrating the viability of a magnetic field cloaking device to create a field free tunnel for an accelerator beam through a transverse magnetic field without disturbing the field outside of it.

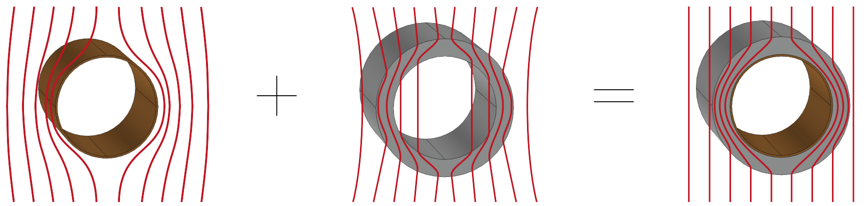


Figure 1: Combining a superconductiong cylinder (left) with a ferromagnetic cylinder (center) yields an effective magnetic field cloak (right). Red lines indicate magnetic field lines.

Introduction

A magnetic field cloaking device creates a volume that magnetic fields cannot penetrate. In contrast to conventional shields for magnetic fields, a cloak does not disturb magnetic field lines around the shielded volume. Therefore, it effectively renders objects inside of it invisible to external magnetic fields and vice versa. Figure 1 illustrates the concept of such a device using the combination of superconducting and ferromagnetic layers. Super currents created in the superconductor (in its superconducting state) push out magnetic field lines. A ferromagnetic layer has the opposite effect on magnetic field lines and draws them in. Therefore, adding a ferromagnetic layer around the superconductor compensates for the field disturbance caused by the superconductor. To achieve complete cancellation of distortion effects, the magnetic permeability μ_r of the ferromagnet must satisfy the relation

$$\mu_r = \frac{R_2^2 + R_1^2}{R_2^2 - R_1^2}\,, \tag{1}$$

where R_1 and R_2 are the inner and outer radii of the ferromagnet, respectively. A first realization of a cylindrical cloak following this concept has been demonstrated in [1] and it is a topic of active research [2].

This project aims at realizing a magnetic cloaking device suitable for the needs of a forward dipole spectrometer at a future Electron Ion Collider, other accelerator-based experiments, and with potential use for medical applications. We assume a cloak for an EIC experiment would have to shield magnetic fields of about 0.5 T over a length of 1 m. During the course of this project, significant progress has been made to fabricate such a device using commercially available materials.

Objectives and Achievements

For this reporting period, we planned to

1. improve our Helmholtz coil field mapping setup to demonstrate the cloak performance without gaps in the mapped field region previously caused by support bars,

2. refine the fabrication of ferromagnetic cylinders (using the established method of mixing epoxy and steel powder in variable ratios to tune the effective permeability of the mixture) to further reduce the residual magnetic field disturbances around our magnetic cloak prototype,

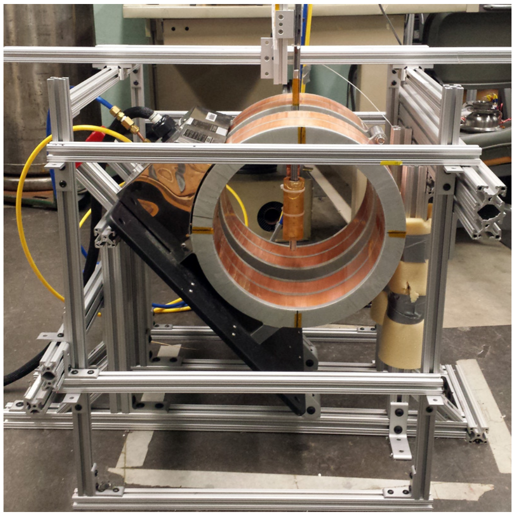
3. test the superconductor tape samples irradiated in the PHENIX IR during Run 15,

4. commission our 1.3 m long superconductor shield made from five layers of 12 mm wide high-temperature superconductor tape (wrapped helically around a 1 inch copper tube) and demonstrate shielding the Van de Graaff beam at Stony Brook University from a transverse magnetic field,

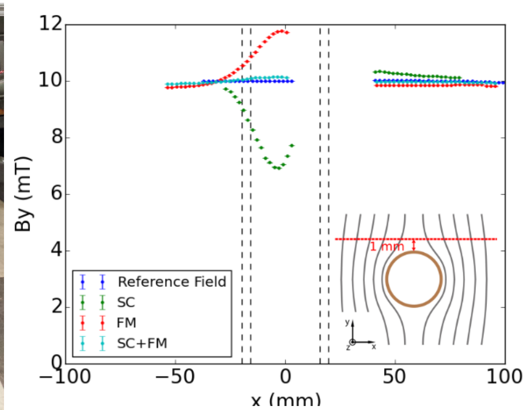
5. collaborate with the BNL magnet division to test the magnetic field shielding performance of high- and low-temperature superconductor samples with fields at up to 0.5 T both at liquid Nitrogen and liquid Helium temperatures,

6. study the potential physics benefits of a conceptual forward dipole spectrometer using a magnetic cloak for an EIC experiment in more details.

We made good progress towards completig these goals. Figure 2a shows our improved Helmholtz field mapping setup. With the new 80/20 frame and the rotation of the magnet, the support bar between the coils does no longer obstruct the passage of the Hall probe when mapping the magnetic field around our cloak prototype. In addition, we added linear bearings for easier movement of the Hall probe. Figure 2b shows a measurement of the magnetic field transverse to a cloak prototype (12 cm long, 1 inch inner diameter, 4 layers of 46 mm American Superconductor superconductor tape) from the previous report. The measurement was done along a line outside the cloak across its center. While the individual superconductor and ferromagnet



(a)



(b)

Figure 2: (a) Our improved Helmholtz coil setup for mapping the magnetic field around our cloak prototypes. (b) Measurement of the magnetic field transverse to a superconducting cylinder, a ferromagnetic cylinder, and a cloak (both cylinders combined), as well as the external field without any cylinders present. The measurement was done along a line outside the cloak across its center.

layers distort the field, their combined effects result in an outside field that closely matches the external field. The measurement clearly shows the gap in the covered range, which we will close with measurements with the new setup.

We thoroughly tested our 1.3 m long superconductor shield (shown in Fig. 3a) in preparation for actual beam tests. We put the shield in a liquid Nitrogen bath inside a beam pipe segment surrounded by beam steering magnets (see Fig. 3b). Figure 4a shows the transverse magnetic field measured at different positions along the center axis of the shield with a single magnet installed. At liquid Nitrogen temperature, the prototype shields 99% of the external 7 mT field. Figure 4b shows the shielding performance for five magnets and its homogeity over the full length of the prototype. Next, we will repeat these measurements using the cryostat inside the beam pipe (instead of the liquid Nitrogen bath) to test this cooling system. By the time of this report, the repairs of the ion source of the Van de Graaff accelerator

(a)

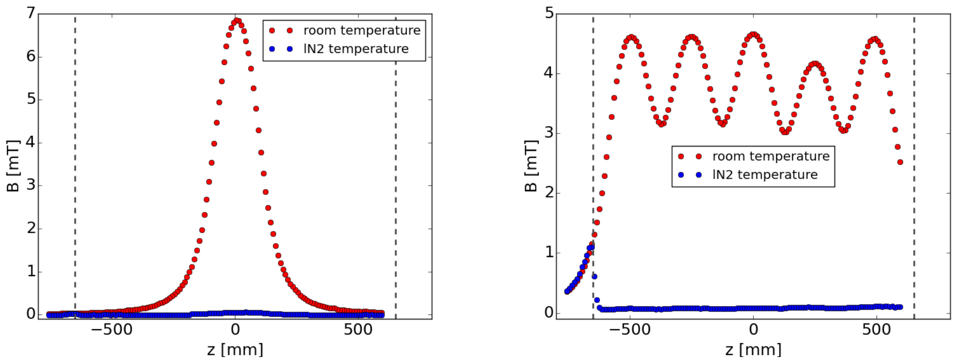
(b)

Figure 3: (a) Our 1.3 m long superconductor shield made from five layers of 12 mm superconductor tape wrapped around a copper tube. (b) Beam pipe segment for testing our 1.3 m superconductor shield with five steering magnets installed.

at Stony Brook are still ongoing. Therefore, we could not test the prototype with actual beam. We expect the repairs to be completed early January 2016 and are ready to do the test as soon as beam becomes available. We are exploring the option to use the Van de Graaff accelerator at BNL as an alternative option should the repairs at Stony Brook be delayed further.

Recent discussions with the BNL-SMD (Superconducting Magnet Division) revealed that the magnets they initially suggested us to use for the high-field tests with liquid Nitrogen cooling are not available to us any more. Our new plan is to design and procure a steel yoke that we can use with one of the BNL-SMD superconducting coils (see Fig. 5a) to create a magnetic field to test the shielding of the high-temperature superconductor tape up to 0.5 T. In addition, it appears that any tests involving liquid Helium are not possible within our current EIC R&D budget for this project. Therefore, we currently have no option to test the shielding performance of our high-temperature superconductor at liquid Helium temperatures, or to test the low-temperature NbTi/Nb/Cu superconductor sheets we procured last summer at all.

We have not yet tested the irradiated superconductor samples and studied the potential physics benefits of a conceptual forward dipole spectrometer using a magnetic cloak for an EIC experiment in more detail due to lack of



(a) (b)

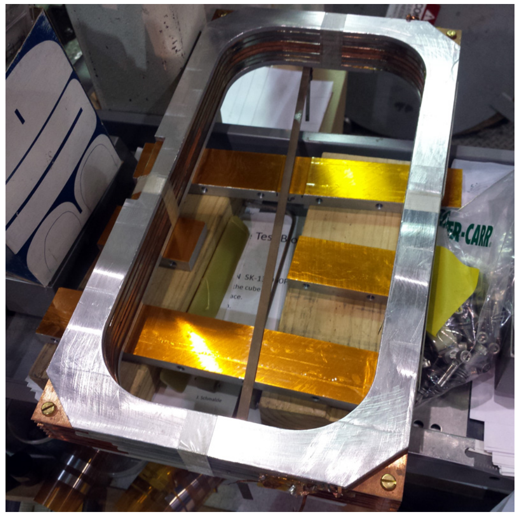
Figure 4: Transverse magnetic field B as a function of the position z along the center axis of our 1.3 m log superconductor shield at room temperature (no shielding) and liquid Nitrogen temperature (superconducting state) for (a) one magnet and (b) five magnets installed. The dashed lines indicate the range covered by the superconductor. Cooling is done by filling the beam pipe segment with liquid Nitrogen.

manpower and plan to do so before the next report.

Future

We will test the 1.3 m superconductor shield as soon as the Van de Graaff accelerator at Stony Brook becomes operational again. We are exploring the option to use the Van de Graaff accelerator at BNL as an alternative option should the repairs in Stony Brook be delayed further. We also intend to do the liquid Nitrogen tests at higher fields at BNL soon. We are still looking for options to do the tests with liquid Helium cooling.

For the longer-term future, we plan to work on a more detailed technical design of how a magnetic field cloak could integrate into a dipole-based forward spectrometer for an EIC detector and explore ways to collaborate with BNL CAD for achieve this. In addition, we have begun to explore the option to use our cloak prototypes not only for shielding external fields, but also to maintain constant internal fields, which would open up possible applications in the transport of polarized He3 for the polarized He3 ion source at BNL or medical imaging. First measurements look promising and we plan to explore



(a)

Figure 5: Superconducting coil at BNL-SMD (17" long, 9.125" wide, 2" thick).

this further.

Manpower

The results presented in this report were obtained by a group of 13 Stony Brook undergraduate students working part-time. For the first month of this reporting period, an MSI (Master of Scientific Instrumentation) student was still working on this project as well before graduating. In addition, one Stony Brook post-doc spent about 10% time training and supervising students and coordinating activities. Only the MSI student was funded through EIC R&D funds (July only). We will use our approved EIC R&D budget for undergraduate students during summer 2016.

External Funding

No external funding was obtained for this project. All results presented in this report have been accomplished with EIC R&D funds only.

Publications

- Raphael Cervantes, *A Comapct Magnetic Field Cloaking Device*, MSI thesis, Stony Brook University, August 2015.
- We are working toward publishing our results in a peer-reviewed journal.

Bibliography

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[2] Jianfei Zhu, Wei Jiang, Yichao Liu, Ge Yin, Jun Yuan, Sailing He, and Yungui Ma. Three-dimensional magnetic cloak working from d.c. to 250khz. *Nat Commun*, 6, 11 2015.